Toepler, Max

Limiting Potential Difference for Electric Discharges in Air at Atmospheric Pressure

ADVISORY COMMITTEE FOR AERONAUTICS.

Special Committee on the Electrification of Balloons.

LIMITING POTENTIAL DIFFERENCE FOR ELECTRIC DISCHARGES IN AIR AT ATMOSPHERIC PRESSURE.—BY MAX TOEPLER. (" *Annalen der Physik,*" *Vierte Folge, Band* 7. 1902. *No.* 3. *pp.* 447-493.)

Translated for the Committee by MISS V. COCKBURN.

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LIMITING POTENTIAL DIFFERENCE FOR ELECTRIC DISCHARGES IN AIR AT ATMOSPHERIC PRESSURE.

By Max Toepler.

(*Annalen Der Physik. Vierte Folge, Band* 7. 1902. *No.* 3. (*Pp.* 477–493.))

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The flow of electricity across the gap between two electrodes may, as is known, assume very diverse forms. To obtain all positive and negative forms of discharge as pure as possible a flat plate opposed to a small (ball-shaped) electrode should be used. The form of the discharge is, in the majority of cases, determined unequivocally by the sparking distance and the current as has already been demonstrated.* For sparking distances between 2 and 10 cms., as the current increases for *positive* discharge (small anode and plate-like cathode) there appear in succession : Non-luminous electric flow, glow, brush, brush-arc and flame arc—and similarly for negative discharge (small cathode, flat anode). If the electrode-capacity† of the two sides of the spark gap is not negligibly small, a transient *discontinuous* flow occurs at all transitions between the two forms of discharge (a series of separate brushes, &c., and finally a stream of sparks).

The "characteristic"—*i.e.*, the potential difference between the electrodes as a function of the current—has the typical form shown in Fig. 1A and Fig. 1B for positive and negative discharge respectively in accordance with my earlier measurements.

The representation of the characteristic given in outline in the figure holds only for the case already thoroughly investigated, of a very blunt *point* opposed to a plate, and for sparking distances of about 2–10 cms. ; the capacity is assumed to be small. An increase of the "*electrode-capacity*" broadens to any great extent only the region of discontinuous discharge, and then almost entirely towards the side of higher current values. Therefore changes in the *sparking distance* and above all in the *size of the electrode* opposed to the plate have a very important influence on the course of the characteristic.

In the present work I have endeavoured to establish the dependence of the *limiting pressure* of individual discharge forms

* M. Toepler, *Ann. d. Phys.*, 2, p. 560. 1900.

† I define "electrode-capacity" as the electrostatic capacity of that part of the conducting circuit which is in good metallic connection with the place of entry of the electricity into the gap.

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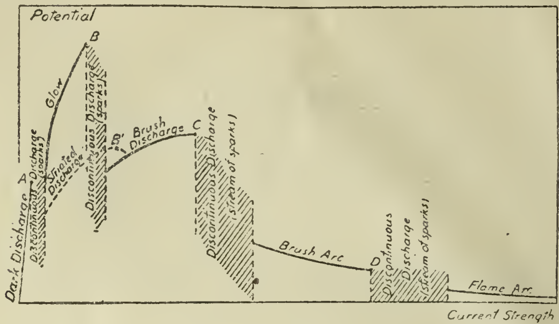
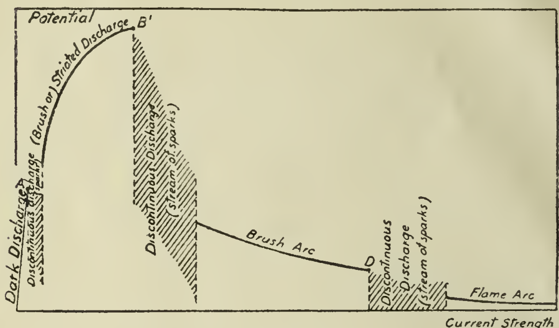
as well as the value of the potentials denoted in Figs. 1A and 1B by A, B, C, D on the sparking distance and size of the electrodes





FIGS. 1A AND 1B.

as far as changes in the constant, arbitrarily variable, current from a 60-plate influence machine permitted.*

I have laid special emphasis on determining also the limiting potential for the case where the supply of electricity to the electrodes is possibly not constant but discontinuous.† As was remarked previously,‡ *striated discharge* then replaces positive glow or negative brush discharge. In Fig. 1A the characteristic follows the course shown by the broken line and the limiting potential B′ for the striated discharge takes the place of the limiting potential B for glow.

* Often in these previous values only the " limiting potential difference for non-luminous discharge " or the " starting potential difference," also called " discharge potential difference " (A in Figs. 1A and 1B) has been examined, *i.e.*, that potential whereby a flow of electricity accompanied by luminosity takes place from the (small) electrode ; our knowledge on this point is very incomplete, especially do we lack data concerning the above-mentioned case of a broad plate opposed to a small ball electrode.

† For this a very small spark gap (only about 0·05 cm. long) was included in the lead to the small electrode. If one understands, as in my earlier work, by *nearly* continuous discharge, one such that rhythmic or even irregularly alternating current leaves at least the *form* of the discharge unchanged, then by introducing the small spark one can speak of nearly continuous discharge in the chief spark gap and also of the *given limiting potential* by allowing a certain amount of latitude, about ± 1,500 volts.

‡ See l.c., p. 596.

The knowledge of the limiting potential differences is of special interest also, as each of them under some circumstances may assume the rôle of a sparking potential difference ; the establishment of the limiting potential throws light (as will be seen later) on many peculiarities in connection with sparking potential up to now unexplained.

I.

Experimental Arrangements.—The experimental arrangements set forth diagrammatically in Fig. 2* differ from those used before.† M represents a 60-plate influence machine, f the chief spark gap with the spherical electrode k,‡ and the flat electrode g (a glass plate, of which a circular area 60 cm. in diameter is covered with tinfoil) ; ϕ is a spark gap which can be easily regulated (0·05 cm. long, between brass balls 2·5 cms. in diameter) and B is a screen.

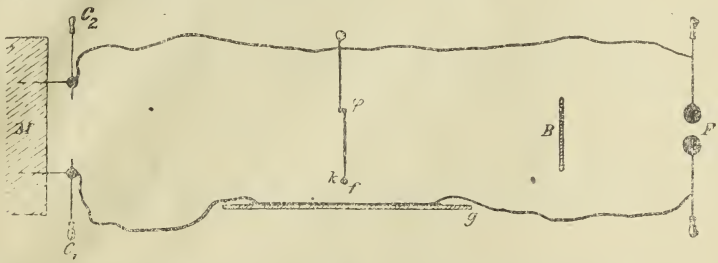


Fig. 2.

The determination of the limiting potential difference in f was made by adjusting a spark gap F (between two brass balls 6 cms. in diameter) inserted near f so that the smallest gap was established, which, when diminished, caused a discharge to take place across the gap. In the tables, besides the distance F thus obtained, is also added the corresponding potential difference in volts.§

Positive Starting Potential Difference.
(A in Fig. 1a.)

For the determination of the values given in Table I the spark ϕ ($= 0·05$ cm.) was inserted. In consequence all the values appear somewhat too high‖ : the introduction of ϕ renders

* The distance between F and f as well as between f and M is not shown to scale in the figure ; they should be longer, in fact more than 2 m.

† See l.c., p. 595, Fig. 8.

‡ The lead to k was formed of a brass rod which was 0·2 cm. in diameter at k and at a distance of 5 cms. from k widened to 0·5 cm.

§ For details referring to fundamental values see l.c., p. 613.

‖ Some familiar measurements showed that the differences in the values of the potential measured with or without the spark inserted amounted to about 1,500 volts on the average.

Since no attempt was made in the measurements in the present work to obtain accurate values but only a general idea of the relative magnitude of the different limiting potentials at electrodes of different sizes, the influence of the inserted spark gap as well as of the barometric height on the values of the limiting potential may be regarded as negligible.

the observation of the first trace of luminous discharge (brush, &c.) easier than when constant current is used.

Table I.

Positive Starting Potential Difference.

Chief sparking distance f in cm.		2·5	5·0	7·5	10·0	12·5	15·0
Diameter of Anode, d = 0·5 cm.	F in cm. ...	0·60	0·70	—	—	—	< 1·03
	in volts ...	20,400	23,500	—	—	—	<33,500
,, ,,	F. in cm. ...	0·85	1·00	1·15	—	—	< 1·45
	in volts ...	28,100	32,600	36,900	—	—	<45,100
,, ,,	F in cm. ...	1·07	1·28	1·48	—	—	< 1·98
	in volts. ...	34,700	40,500	45,900	—	—	<58,400
,, ,,	F in cm. ...	1·28	1·57	1·73	1·90	—	< 2·33
	in volts ...	40,500	48,300	52,300	56,500	—	<66,400
,, ,,	F in cm. ...	1·56	1·95	2·25	2·58	2·82	< 3·15
	in volts ...	48,000	57,700	64,600	71,800	76,700	<83,100
,, ,,	F in cm. ...	1·72	2·40	2·84	—	—	—
	in volts ...	52,100	67,900	77,100	—	—	—

The high values in the *last* vertical column show that here the influence of the lateral supply lead on the distribution of the potential in the chief spark gap f is already noticeable.

Limiting Potential for Positive Glow.

(B in Fig. 1a.)

At a polished *metal* sphere more than 1·5 cms. in diameter I could obtain no glow even with fairly constant current; with electrodes of 1·5 cms. diameter it appeared only transiently. To make it complete the values obtained by graphic interpolation of earlier measurements for small electrodes may be given.*

Limiting Potential Difference (*in volts*) *for Positive Glow.*

Chief sparking distance f in cms.	2·5	5	7·5	10	15	25
Anode = blunt point ...	28,000	42,000	53,000	62,000	74,000	90,000
,, = ball, d = 0·5 cm....	39,000	62,000	79,000	93,000	—	—
,, = ball, d = 1·0 cm....	43,000	66,000	83,000	—	—	—

Limiting Potential Difference for Positive Striated Discharge. (B′ in Fig. 1a.)

The limiting potential difference for positive striated discharge,† which is formed in place of positive glow on the introduction of

* Only the value 90,000 volts at 25–26 cms. sparking distance for the point (curvature 0·1 cm.) used before, is a new measurement.

† Striated discharge is made up of numberless short filiform brushes. See l.c., p. 618.

the spark gap ϕ, is considerably smaller than the limiting potential for positive glow (see l.c., Fig. 9, also Fig. 1A of the present work). The insertion of the spark causes a diminution, so to speak, in the height of the potential crest, which has to be overcome to obtain positive brush, by increase of the current. How large, or rather how small, the limiting potential difference for positive striated discharge is in individual cases depends on the way in which the irregular current is supplied to the electrodes. By introducing a spark ϕ 0·05 cm. long and increasing the mean current *very* slowly the limiting potential under discussion was about 2,000–3,000 volts smaller than the limiting potential for positive brush (C in Fig. 1A) given later (in Table III).

By a sudden increase of current (rapid separation of the conductors of the machine C_1 and C_2 in Fig. 2) one obtains still smaller potential differences in order to cause the momentary appearance of a brush discharge bridging right across the gap and sometimes also sparks. The *smallest values of the limiting potential for striated discharge* which I have been able to observe are collected together in the following table :—

TABLE II.

Limiting Potential Difference for Positive Striated Discharge.

Chief sparking distance f in cm.		5·0	7·5	10·0	12·5	15·0	17·5
Diameter of anode, d = 0·5 cm.	F in cm.	0·60	1·05	1·40	1·95	2·4	3·0
	in volts.	20,400	34,000	43,800	57,700	67,900	80,200
,, ,, d = 1·0 cm.	F in cm.	—	1·15	1·50	2·0	2·5	3·1
	in volts.	—	36,900	46,400	58,900	70,000	82,100

The limiting potential difference for striated discharge is, under similar experimental conditions, hardly at all dependent on the diameter of the anode.

THE LIMITING POTENTIAL DIFFERENCE FOR POSITIVE BRUSH.

(C in Fig. 1A.)

Repeated measurements gave the following concordant values :—

TABLE III.

Limiting Potential for Positive Brush Discharge.

Chief sparking distance f in cm.		2·5	5·0	7·5	10·0	12·5	15·0
Diameter of anode, d = 0·5 cm.	F in cm.	0·69	0·98	1·55	1·90	2·36	2·9
	in volts	23,300	32,000	47,800	56,500	67,000	78,300
,, ,, d = 1·0 cm.	F in cm.	No brush discharge.		1·50	1·89	2·40	2·95
	in volts			46,400	56,200	67,900	79,200
,, ,, d = 1·5 cm.	F in cm.	No brush discharge.		1·52	1·89	2·42	3·0
	in volts			47,000	56,200	68,400	80,200
,, ,, d = 2·0 cm.	F in cm.	No brush discharge.			1·94	2·48	3·1
	in volts				57,500	69,700	82,100
,, ,, d = 3·0 cm.	F in cm.	No brush discharge.					3·23
	in volts						84,600

As with striated discharge so also with positive brush discharge it is as a rule only capable of continued existence with potential differences greater than the starting potential.*

The limiting potential difference for brush discharge is nearly the same within wide limits and almost independent of the electrode-capacity, as can easily be shown by introducing a Leyden jar.

The facts resulting from Table III are very striking: *The limiting potential difference for positive brush* is, at least to the first approximation, *independent of the size of the anode from which the brush discharge proceeds.*

Negative Starting Potential Difference. (A in Fig. 1b.)

Here also the spark gap ($\phi = 0{\cdot}05$ cm.) was inserted near the chief gap; the small electrode was the cathode and the plate the anode.

Table IV.

Chief sparking distance f in cm.		1·75	2·50	3·75	5·00	6·75
Diameter of cathode,	F. in cm. ...	0·56	0·64	0·67	0·71	—
$d = 0{\cdot}5$ cm. ...	in volts ...	19,100	21,700	22,700	24,000	—
Diameter of cathode,	F. in cm. ...	0·77	0·87	0·99	1·03	—
$d = 1{\cdot}0$ cm. ...	in volts ...	25,800	28,700	32,300	33,500	—
Diameter of cathode,	F. in cm. ...	0·97	1·05	1·19	1·32	—
$d = 1{\cdot}5$ cm. ...	in volts ...	31,700	34,100	38,000	41,600	—
Diameter of cathode,	F. in cm. ...	1·08	1·23	1·38	1·53	1·55
$d = 2{\cdot}0$ cm. ...	in volts ...	35,000	39,100	43,200	47,200	47,800
Diameter of cathode,	F. in cm. ...	1·24	1·55	1·68	1·95	2·10
$d = 3{\cdot}0$ cm. ...	in volts ...	39,400	47,800	51,200	57,700	61,300
Diameter of cathode,	F. in cm. ...	1·32	1·66	2·23	2·35	2·68
$d = 4{\cdot}0$ cm. ...	in volts ...	41,700	50,600	64,300	66,800	74,000

Within the limits of experimental error the negative starting potential differences have the same value as the positive, as is already known for other combinations of electrodes.

Limiting Potential for Negative Brush Discharge.

A *single* well-developed negative brush discharge is easily formed at a pointed electrode; with a spherical electrode even with constant current it is only formed under exceptional circumstances and transiently. The limiting potential cannot therefore be established.

* Brush arcs and, even more readily, flame arcs, are capable of continued existence at potentials which are smaller than the starting potential. If the value of A is greater than B′ or C, one obtains a stream of sparks, till with an adequate mean current, brush arc or flame arc appears.

Limiting Potential Difference for Negative Striated Discharge. (B′ in Fig. 1B.)

A negative striated discharge is also only capable of existing at potential differences larger than the actual starting potential difference.

Table V.

Limiting Potential Difference for Negative Striated Discharge.

Chief sparking distance f in cm.	1·75	2·50	3·75	5·00	6·75
Diameter of cathode, $d = 0·5$ cm. F in cm. ...	0·97	1·31	2·19	3·0	—
in volts...	31,700	41,400	63,400	80,200	—
Diameter of cathode, $d = 1·0$ cm. F in cm. ...	0·85	1·23	2·08	2·75	—
in volts...	28,200	39,200	60,900	75,400	—
Diameter of cathode, $d = 1·5$ cm. F. in cm.	No striated discharge	1·18	1·82	2·65	—
in volts		37,700	54,500	73,300	—
Diameter of cathode, $d = 2·0$ cm. F in cm. ...	No striated discharge.		1·48	2·48	73·3
in volts...			45,900	69,400	786,000
Diameter of cathode, $d = 3·0$ cm. F in cm. ...	No striated discharge			2.09	3·07
in volts...				61,100	81,500
Diameter of cathode, $d = 4·0$ cm. F in cm. ...	No striated discharge.				
in volts...					

Within the range covered by the experiment the limiting potential difference increases practically in proportion to the sparking distance. It is a striking fact that this limiting potential has, with the same sparking distances, a *smaller* value with large electrodes than with small ones.

The values in the table were obtained with the spark gap ($\phi = 0·05$ cm.) inserted. With ball-ended electrodes, a striated discharge almost always appeared, as already mentioned, when the current was *constant* ($\phi = 0$). The secondary spark gaps for negative striated discharge for constant and for irregular current supply are distinguished, as observations show, only by an amount corresponding to the length of the inserted spark ; the real limiting potentials are therefore practically the same in the two cases.

Limiting Potential Difference for Brush Arc. (D in Fig. 1A and 1B.)

The available current was not sufficient to reach the upper limits of existence for a positive or negative brush arc.

II.

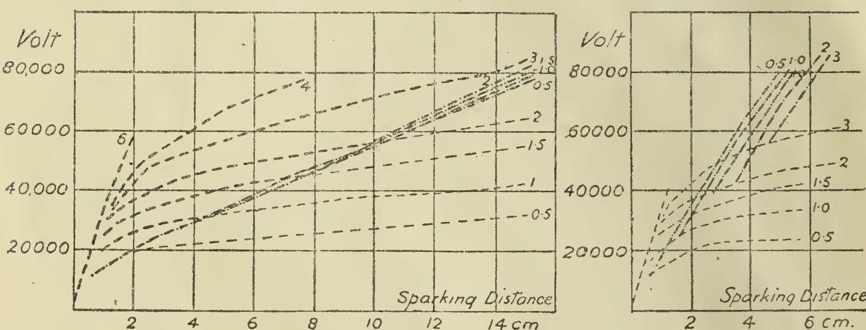
Sparking Potential Difference.

Sparks may be formed as shown in Fig. 1A and 1B (when the electrode-capacity is sufficiently large) generally at the

beginning of luminous discharge and later at the transition of any form of luminous discharge into the succeeding one. To avoid ambiguity in the following we shall understand by "sparking potential difference" that limiting potential at which sparks are formed *for the first time* as the current is increased from zero.*

Only in the case of *irregular* current supply shall I go more thoroughly into the sparking potential in the narrow sense.

For positive discharge the sparking potential is identical with the starting potential for small sparking distances (A in Fig. 1A) and for larger sparking distances with the limiting potential for brush (C in Fig. 1A)—the fall of potential at the transition from positive striated discharge to brush (B′ in Fig. 1A) is usually so small that sparks are seldom formed. In Fig. 3A based on Tables I and III the curve of the starting potential difference for increasing sparking distance is a broken line, and that for brush discharge a dot and dash line; so long as either is at the same time the *sparking* potential the curve is drawn thicker. The figures on each curve give the diameter (in cm.) of the spherical anode used in determining the values (cathode = a circular plate 60 cms. in diameter). *The curve of the sparking potential as a function of the sparking distance possesses, as is shown in the figure, a bend for each size of anode, where the spark formation*



FIGS. 3A AND 3B.

changes into the limiting potential for brush. The bend lies at about that sparking distance which is equal to five times the diameter of the anode.

With *negative* discharge (see Fig. 3B and Tables IV and V) the meaning of a sparking potential difference with increasing anode changes from the starting potential (broken line) to the limiting potential for *striated* discharge (dot and dash in Fig. 3B). *Here also for each cathode there is a bend in the curve of the sparking potential difference.*

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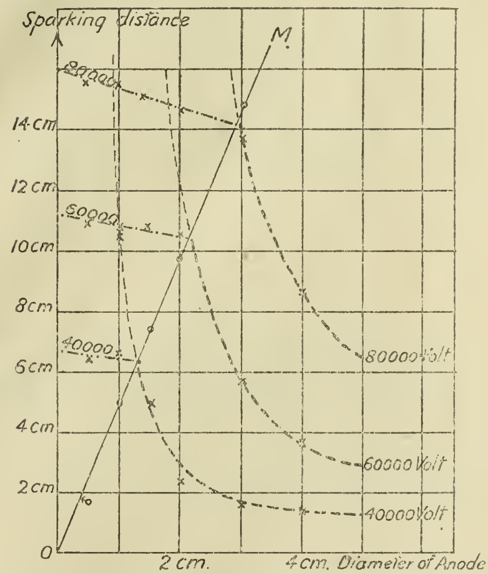
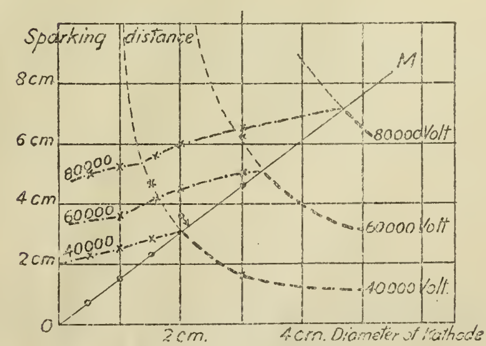
* See l.c., p. 609, *et seq.* It should be noted that the sparking potential difference in the narrow sense given is in most, but *certainly not* in all cases, identical with the *greatest* limiting potential for the experimental conditions chosen.

Finally the observations may be set forth in Fig. 4A and 4B in a manner that renders them especially clear for many purposes. Imagine a system with three co-ordinate axes, representing the diameter of the smaller electrode, the sparking distance and the potential difference. Let the first two lie in the plane of the paper and the projections of the *curves* of *equal potential* be drawn between them (these are analogous to the contour lines in maps, with length and breadth as co-ordinates, except that here *several* limiting potentials may correspond to a given sparking distance and size of electrode, so that one should think of a geological map in which the bounding surfaces of different formations are represented by contour lines). The curves of equal starting





FIGS. 4A AND 4B.

potential are represented by a broken line, those for equal limiting potential for positive brush (in Fig. 4A) or negative striated discharge (in Fig. 4B) by a dot and dash line. The line OM

connecting the points of intersection of curves of equal value of the two systems is almost straight in both figures. In the region to the right of OM the sparking potential difference is identical with the starting potential difference ; in that to the left, usually with the given limiting potential for positive brush or negative striated discharge ; as in Figs. 3A and 3B the curves in Figs. 4A and 4B are in heavier type so long as they represent sparking potential as well.

The curves of equal limiting potential for positive brush or negative striated discharge are practically straight lines.

The curves of equal starting potential show, as one can see from Fig. 4A, another characteristic which is deserving of notice. If through the origin O one draws straight lines in different directions cutting the curves of equal starting potential, and if one finds for each of these the ratios between the distances from O to each of the curves, one obtains for each straight line the *same* value of these ratios. If also one knows one of the curves under discussion, it is sufficient for the construction of any other to know *one point* on it.

III.

Empirical Formulæ.

The purely empirical formula given below facilitates a rapid approximate calculation of the value sought ; it is practicable to choose whole numbers as constants for the formula even when by the introduction of fractions a somewhat closer approximation of the experimental data was aimed at.

Positive Starting Potential Difference. (A in Fig. 1A.)

Each of the hyperbolic curves of equal starting potential in Figs. 4A and 4B is approximately asymptotic, as is known, when the sparking distance is infinitely great ($f = \infty$) with a given, smallest, limiting value of d and also asymptotic on the other side when $d = \infty$ and f has a minimum value.

In the first limiting case (infinitely large spark gap) the starting potential difference (across an infinite distance) may be expressed by the formula :—

$$A_{f=\infty} = 300 \, . \, d \left[96 + \frac{6A}{\sqrt{d}} \right] \text{ volts,}$$

where d = the diameter of the electrode. One obtains, therefore, as values for the part in brackets :—

When d =	0·5	1·0	2·0	3·0	4·0	5·0
Observed*	182	160	140	—	—	Ca. 125
Calculated	186·5	160·0	141·3	133·0	128·0	124·6

* See A. Heydweiller, *Wied. Ann.*, 48, p. 230. 1893.

By means of the formula given one can calculate for every curve of equal starting potential the value of d for the corresponding vertical asymptote (very large sparking distance).

If one takes the statement made at the end of the preceding section on the constancy of the ratios as valid for all sparking distances and all sizes of anode, then it follows from the interdependence of d and $A_{f=\infty}$ that the value of the starting potential is given for all cases by the equation :—

$$A = \phi\left(\frac{f}{d}\right)d\left(96 + \frac{64}{\sqrt{d}}\right)$$

where ϕ represents a function of the *ratio* $f : d$ *alone*, *i.e.*, sparking distance divided by the diameter of the anode. The experimental data do not seem to me sufficiently complete to provide a formal expression for this function based on the isolated values easily calculated from the table.

Along the straight line OM in Fig. 4A, *i.e.*, for $f : d = 4{\cdot}8$, $\phi\ (f : d) = 206$, as shown by experiment.

Limiting Potential Difference for Positive Glow.
(B in Fig. 1A.)

The course of the limiting potential for glow is expressed, in very good agreement with the observations, by means of the following formula. For the blunt point :—

$$B = 120{,}000\,\frac{f}{f+9}\ \text{volts}$$

when the anode is 0·5 cm. in diameter :—

$$B = 180{,}000\,\frac{f}{f+9}\ \text{volts}$$

when the anode is 1·0 cm. in diameter :—

$$B = 190{,}000\,\frac{f}{f+9}\ \text{volts.}$$

The validity of this formula is proved up to potential differences of 90,000 volts.

Limiting Potential Difference for Positive Brush Discharge. (C in Fig. 1A.)

The resemblance which exists between the formation of sparks in the gap by a brush discharge which completely fills the gap and the transient spark, investigated earlier,* on a polished glass surface whose path is prepared by a plain brush, suggest using the same type of formula from which the length of the transient spark can be calculated within wide limits (to 120 cms.).

* See M. Toepler, *Wied. Ann.*, 66, p. 1061. 1898.

If C is the limiting potential difference for a positive brush discharge (in volts), f the sparking distance (in cms.), one can put for *small* anodes :—

$$C = 450{,}000 - \log\left(\frac{f}{30} + 1\right) \text{ volts.}$$

One obtains for example :—

Sparking Distance f in cm.	Potential Difference C in volts.	
	Calculated.	Observed.
5	30,700	ca. 32,000
10	56,250	ca. 56,000
15	79,200	ca. 79,000
18	91,800	ca. 91,000
30	135,500	—
90	270,900	—

As far as the measurements go the observed and calculated values are in sufficiently good agreement.*

At larger electrodes the formation of the brush discharge appears (especially the formation of the corona) somewhat difficult and the limiting potential is raised ; but one can foresee that when $d = \infty$, it will approach an upper limit. Certainly in practice this extrapolation has no value so long as we are unable to obtain a brush discharge with potential differences *smaller* than the actual starting potential. It is sufficient to present the curves obtained experimentally, given by a dot and dash line in Fig. 4A, as straight lines, or as parts of curves having the abscissæ as asymptotes. The latter yields the simpler formula :—

$$C = 450{,}000\left(\log\frac{f}{30} + 1\right)\left(1 + \frac{d}{80}\right) \text{ volts.}$$

The formula holds for sparking distances f between 2 and about 20 cms. and for anodes of diameters d ranging from 0·1 to 3 cms.

Negative Starting Potential Difference. (A in Fig. B.)

These are, as was mentioned, equal to the positive within the limits of experimental error.

Limiting Potential Difference for Negative Striated Discharge. (B′ in Fig. 1B.)

In the small region (sparking distances up to 7 cms. and diameters of cathode between 0·5 and 1·5 cms.) the simple formula suffices :—

$$B' = 17{,}000\, f\,(1 - 0{\cdot}08d) \text{ volts.}$$

It may be foreseen that for large sparking distances the potential would finally increase more slowly in proportion to the spark gap.

* See my earlier account of the limiting potential difference at a blunt point.

The experimental results here presented give a very complete survey of the dependence of the limiting potential or sparking distance and size of electrode.

For discharge of a *positive* character any considerable change in the form obtained for *very large* spark gaps is not to be expected. Owing to our very inadequate knowledge concerning high limiting potential for brush and striated discharge, the course of negative discharge for large sparking distances cannot be foreseen. It seems necessary to first produce and observe the existent negative discharge form* analogous to positive brush discharge ; for this it would be necessary to employ machines which for the same load yield *much higher* potential differences than that of the machine that I used.

DRESDEN, *December 28th*, 1901.

(*Presented December 29th*, 1901.)

* Under special circumstances I could observe such forms of discharge ; see the description in *Ann. d. Phys.*, 2, p. 576, Fig. 5, 1901 ; also many St. Elmo's fires (see *e.g.*, *Mitt. d. Naturw. V. Steiermark*, 1889, p. 424) are considered as a similar form of discharge.

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